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AIR WEATHER SERVICE

TECHNICAL REPORT 105-132

PRELIMINARY RESULTS OF PROJECT CLOUD TRAIL

FEBRUARY 1956

HEADQUARTERS
AIR WEATHER SERVICE
MILITARY AIR TRANSPORT SERVICE
UNITED STATES AIR FORCE
Washington 25, D. C.

AWS TECHNICAL REPORT
NO. 105-132

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FOREWORD

1. Purpose. To provide preliminary results of Project CLOUD TRAIL for Air Weather Service forecasting, observing, and climatological activities.

2. Scope. This Report presents findings based on winter and spring data collected in Project CLOUD TRAIL. The Project has provided accurate observations of the occurrence or non-occurrence of contrails, cirrus clouds, and high-level turbulence. The data have been used as a basis for improved methods of forecasting contrails, cirrus clouds, haze, and turbulence at the heights of operation of jet aircraft as well as for constructing contrail probability curves which do not require the specification of relative humidity. Section IV of this Report presents a test (based on CLOUD TRAIL data) of the accuracy of the method in AWS TR 105-110, June 1953, for estimating the height of cirrostratus clouds. Individual final reports and/or manuals are planned on the phases covered in the various sections of this Report.

3. Additional Copies. This Technical Report is stocked at Headquarters MATS, AG/Publications. Additional copies may be requisitioned from Headquarters Air Weather Service, ATTN: AWSAD, in accordance with AWS Regulation 5-3.

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I. INTRODUCTION

Project CLOUD TRAIL was established within the Air Defense Command in conjunction with Air Weather Service to collect high-level weather information from jet aircraft. The aircraft were to accumulate sufficient data to serve as a basis for improved methods of forecasting contrails, cirrus clouds, haze, and turbulence at the heights of jet aircraft operation. To obtain these data, the observational phase of the Project ran from 1 December 1954 to 15 December 1955. During this period 36 fighter-interceptor squadrons based in the United States collected data over 23 upper-air sounding stations. The procedure employed was as follows:

a. Each day from approximately one hour before to two hours after 1530Z, two aircraft were vectored to a point 25,000 feet above an upper-air sounding station. The aircraft then climbed to the maximum altitude obtainable, maintaining position within 30 miles of the station.

b. The wingman observed whether or not the lead aircraft produced exhaust trails and whether they were continuous or intermittent, pronounced or faint, including bases and tops of layers in which the trails formed.

c. The aircraft attempted to penetrate all cirrus and haze layers, avoiding holes in the cloud layers. The leadman estimated the coverage of each such layer in tenths as well as the measured heights of cirrus and haze bases and tops actually penetrated. During the climb he also reported whether or not turbulence was encountered and its intensity, giving the bases and tops of each layer.

Preliminary Project results based on winter and spring data are presented in Sections II through V. Final results will appear in individual reports and/or manuals on the various topics concerned.

II. CONTRAIL-PROBABILITY FORECAST CURVES

Air Weather Service Manual 105-100 presents theoretically-derived curves which indicate the pressure-temperature-relative humidity relationship necessary for contrail formation by the exhaust from jet aircraft (see Figure 1). This graph is composed of three main regions — Yes, Possible, and No. In the Yes region, trails theoretically will form even in completely dry air; in the Possible regions, trails will form provided the relative humidity is above the critical value shown on the graph; in the No region, trails should not form even in an initially saturated environment. Empirical evaluations (AWS TR 105-103, 105-112, and 105-126) have verified the accuracy of the Yes and No regions. Lack of relative humidity data has made impossible such an evaluation of the Possible region.

In the Yes and No regions, which would comprise the greatest part of most soundings, the pressure and temperature alone are sufficient to determine whether or not trails will form. A significant portion of almost every sounding, however, lies in the Possible region. Here, relative humidity values must be used in order to issue a forecast. Unfortunately, relative humidity is not measured at the low temperatures where trails form; hence, it must be estimated. Since little is known concerning upper-air humidities, such estimates cannot be considered even as informed guesses. To bypass this obstacle, it was decided to obtain sufficient data to make an empirical study of contrail frequency as a function of pressure and temperature alone. In this way the associated mean relative humidity at each pressure

temperature value is absorbed into the frequency curves. This method does not allow a Yes-No forecast of points falling in the Possible region as would be the case if humidity data were available. It does, however, permit a statement as to the relative frequency (i.e., empirical probability) of contrail formation for any given value of pressure and temperature.

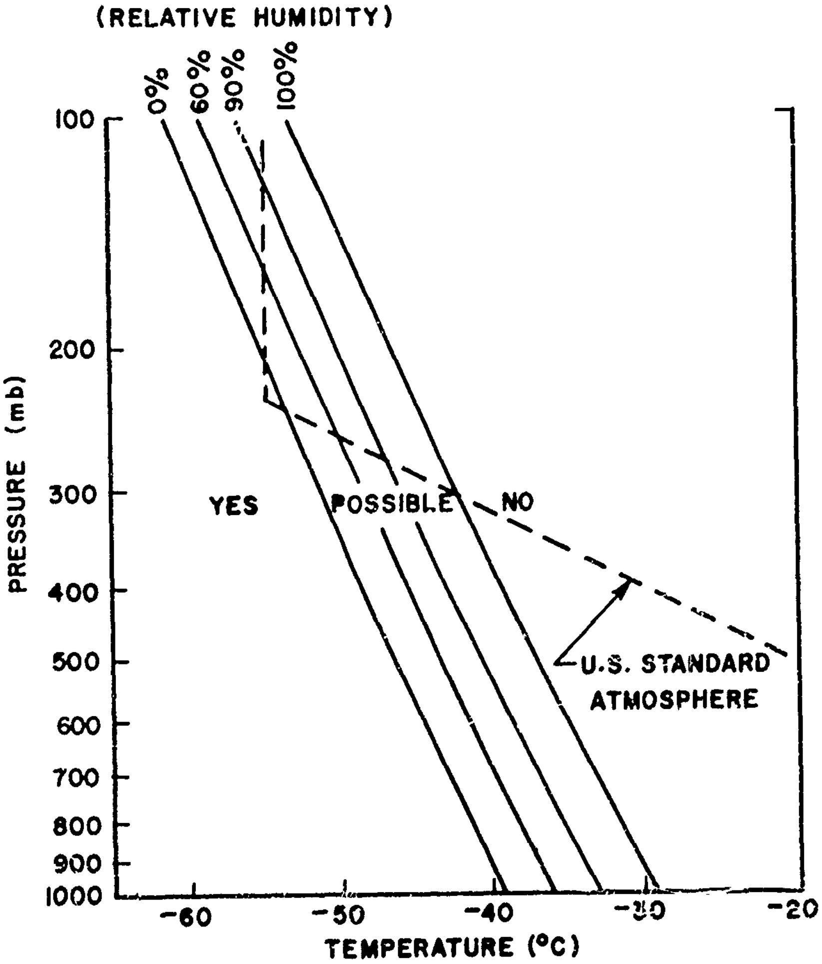

Fig. 1. Graph of the Required Relative Humidity for Contrail Formation as a Function of the Pressure and Temperature of the Environment.

A. Procedure

Project CLOUD TRAIL data are being used for constructing the contrail frequency curves. As the data cards are received by AWS Scientific Services, the associated soundings are plotted from data contained in the Daily Upper Air Bulletins. The contrail, cirrus, and clear air turbulence levels are entered on each sounding. This part of the project has been completed for the winter and spring seasons.

For six selected pressure levels — 350, 300, 250, 200, 175, and 150 mb — the occurrence and non-occurrence of contrails and the associated temperatures were picked off. A tabulation was made of the number of contrail, no contrail, and total cases at each degree of temperature at each pressure level. These data were smoothed using three-degree running totals and the percentage frequency of trails determined for each degree of temperature. A plot of contrail frequency against temperature was made for each pressure level and smooth curves drawn. (See solid curves, Figures 2 and 3; dashed curves are discussed in a later paragraph.) The temperature values for several selected contrail frequencies — 0, 10, 25, 50, 75, 90, and 100% — were picked off, replotted on a pressure-temperature graph, and smooth curves drawn (Figures 4 and 5). For comparison the four theoretically-derived contrail curves from AWSM 105-100 are entered in Figures 2 to 5 as dashed lines.

B. Analysis

Before discussing the individual empirical probability curves shown in Figures 2 and 3, it is useful to consider some of the physical relationships involved. A study of Figure 1 shows that near the 0% relative-humidity curve a small change in temperature is equivalent to a large change in relative humidity. The opposite is true near the 100% curve. Assuming an equal chance for all relative humidity values at every pressure-temperature point, resulting contrail frequency curves would start out flat, then become progressively steeper toward the upper end (Figure 6). If the relative humidity values were evenly distributed, but had a minimum or maximum cut-off above 0 or below 100% respectively, the flattening effect would be reduced (Figure 7). Other irregularities in the atmospheric humidity distribution would influence the probability curves in yet other ways. A normal distribution of relative humidity about a mean of 50% with a standard deviation of 20% results in extreme flattening of the lower ends of the curves (Figure 8). With this distribution, 68% of the cases would fall between 30 and 70% relative humidity; 95% of the cases would fall between 10 and 90% relative humidity.

The empirical probability curves of Figures 2 and 3 show the expected flattening at the lower end. However, the progressive steepening of the remainder of the curves continues only to probability values of 70 or 80%; thereafter, the curves inflect somewhat to the left. It is difficult to explain this flattening of the upper part of the curves on the basis of any reasonable distribution of relative humidity in the atmosphere. It is probably due, at least in part, to temperature errors. Such errors might arise in the radiosonde instrument itself, in the printing of the Daily Upper Air Bulletins,* or in analysis. Time and/or space differences between the balloon and pilot reports also might lead to significant errors

* The curves in Figure 3 are based on checked temperature data, which eliminates observer and transmission errors. No significant decrease in flattening resulted.

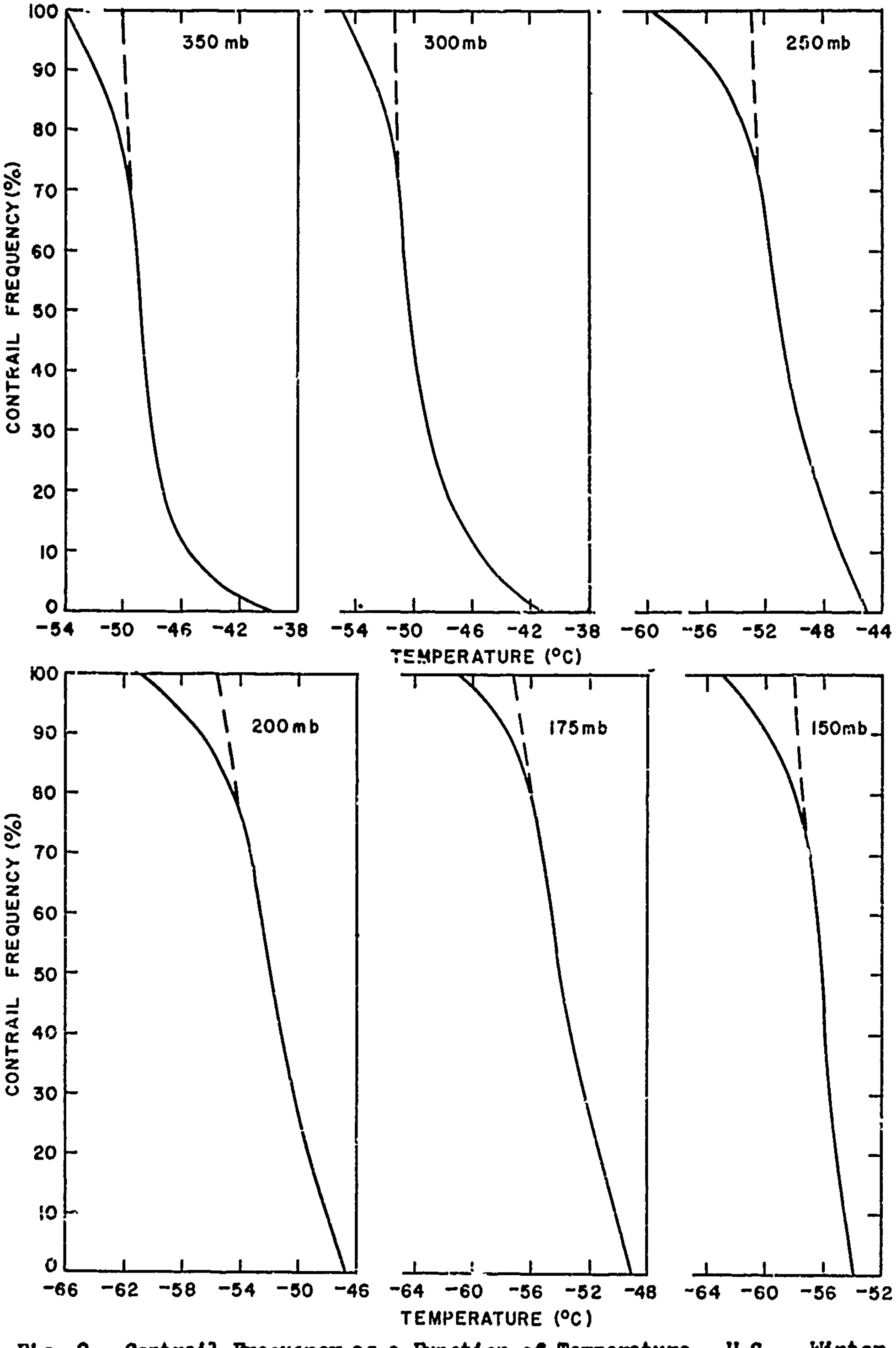

Fig. 2. Contrail Frequency as a Function of Temperature - U.S., Winter.

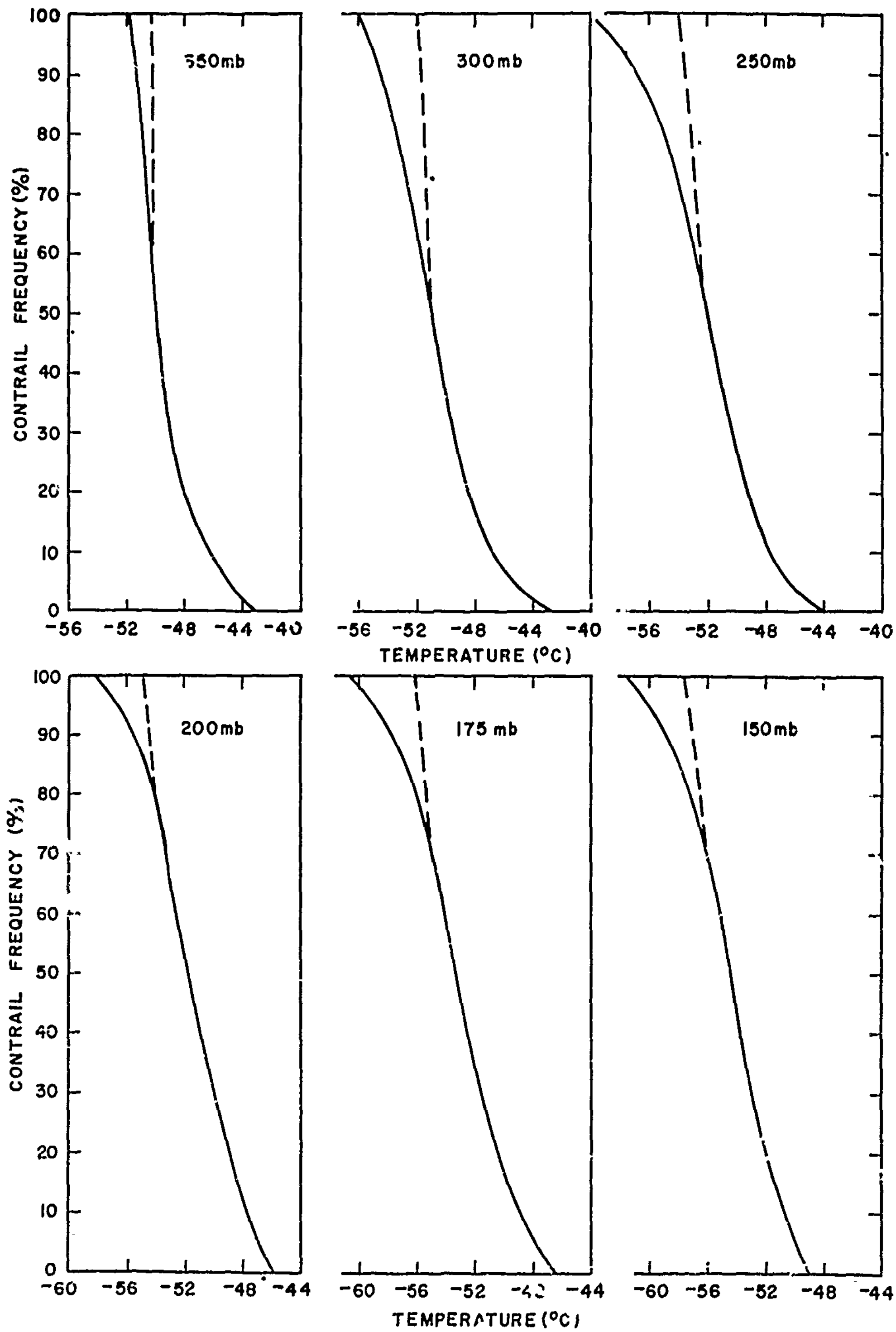

Fig. 3. Contrail Frequency as a Function of Temperature - U.S., Spring.

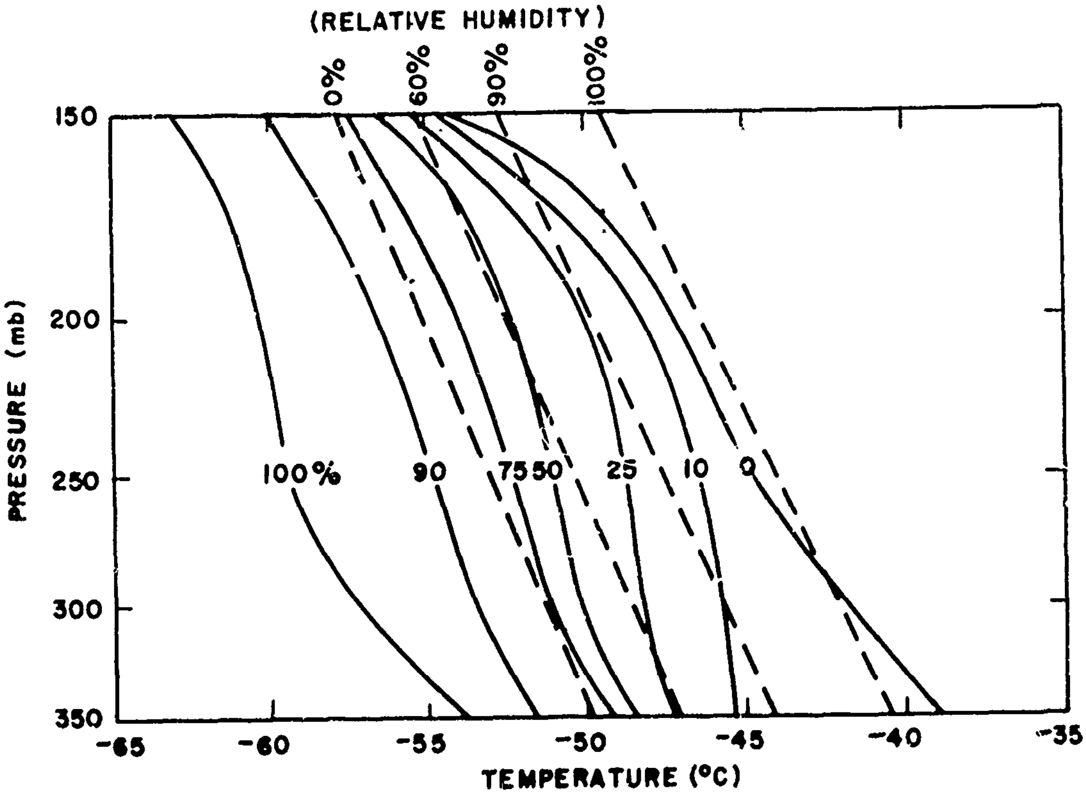

Fig. 4. Contrail Probability as a Function of Temperature and Pressure - U. S., Winter. Solid lines represent observed values of contrail probability. Dashed lines represent minimum values of relative humidity for contrail formation at indicated temperature and pressure.

under certain situations. Temperature errors tend to be self-compensating in the Possible region of the graph, with just as many cases reported too cold as too warm. In the Yes and No regions, however, temperature errors can act in but one direction. Erroneous reports would fall in these regions which properly belong inside the Possible region. This would result in a flattening of both the lower and upper ends of the probability curve. However, as was pointed out earlier, the low probability (high relative-humidity) end of the graph is not very sensitive to small temperature differences; whereas, the high probability (low humidity) end is extremely sensitive to temperature. Hence, the effect of temperature errors would be reflected much more strongly in the upper ends of the curves than in the middle or lower portions.

Any pilot-reporting errors would also mainly affect the upper end of the probability curves. It is much more likely that a pilot or observer might miss a trail that actually exists than report one where none has formed.

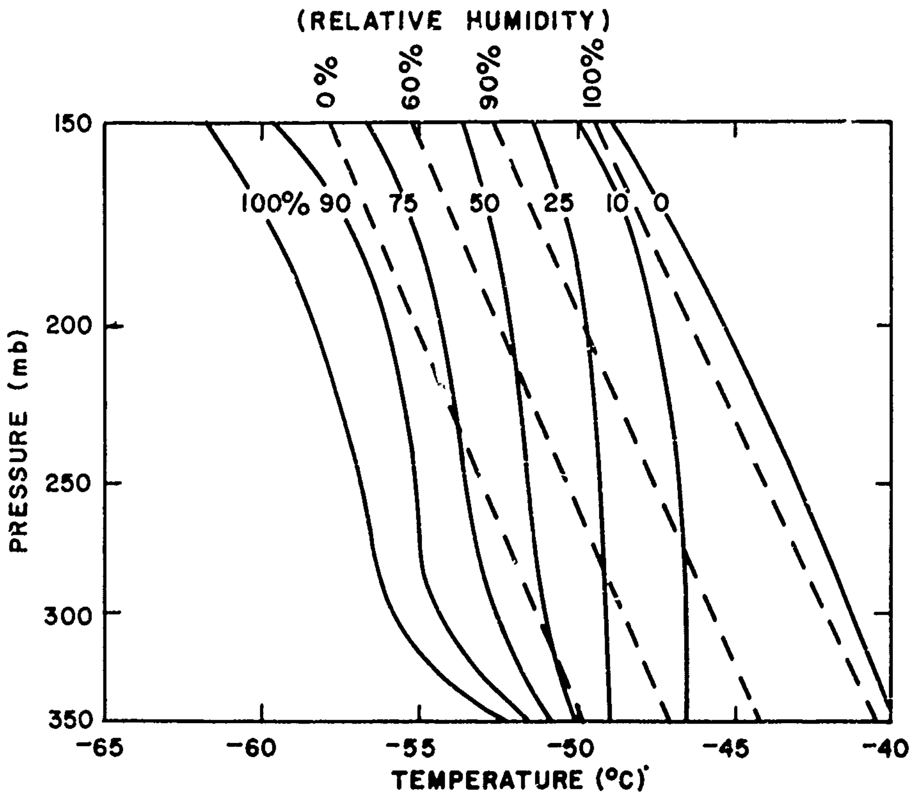

Fig. 5. Contrail Probability as a Function of Temperature and Pressure - U. S., Spring. Solid lines represent observed values of contrail probability. Dashed lines represent minimum values of relative humidity for contrail formation at indicated temperature and pressure.

A final weakness in the curves is a scarcity of data at certain temperatures. It is particularly harmful when data is scarce near the 0 and 100% ends of the probability curves. The lack of data at certain temperatures is not due to an inadequate collection program, but to the normal temperature range which exists in the atmosphere for a given altitude and season. The number of observations available at each pressure-temperature point is shown in Tables I and II. Assuming that a satisfactory sample consists of 20 or more cases, all curves except those for the 300-mb level show some unreliability at one end or the other. The two highest layers are based on rather small samples of data throughout. This does not mean that the curves as a whole are unrepresentative of actual conditions. It does mean that the regions of sparse data are more subject to distortion by any errors that might be present.

Before issuing the final report, the probability curves for all four seasons will be compared with one another to determine the reliability of apparent peculiarities in individual graphs.

TABLE I

Number of Individual Aircraft Observations
at Each Pressure-Temperature Value
-Winter-

Temperature °C	Pressure (mb) 350	300	250	200	175	150
≥ -35	46	2				
-36	22	0				
-37	18	0				
-38	46	1	1			
-39	38	9	3			
-40	43	5	3	3	1	
-41	31	8	3	0	0	
-42	39	18	1	0	1	
-43	31	18	3	0	0	
-44	42	29	3	2	0	
-45	28	34	5	5	1	
-46	23	40	9	5	1	1
-47	14	57	10	8	4	2
-48	11	50	21	11	2	0
-49	15	41	14	9	6	1
-50	7	43	29	10	6	4
-51	2	43	27	14	7	5
-52	3	36	32	8	6	7
-53	0	17	21	17	6	5
-54	3	16	78	11	9	7
-55		8	39	21	16	6
-56		7	51	25	3	4
-57		1	37	16	13	9
-58		1	34	20	13	7
-59		2	29	16	12	9
-60			10	21	13	11
-61			10	15	8	8
-62			6	17	8	7
-63			1	18	11	3
-64			2	14	4	4
≤ -65				32	21	7

NOTE: The temperature range inclosed between the two horizontal lines at each pressure level is the range where, theoretically, contrail formation is determined by atmospheric relative humidity.

TABLE II

Number of Individual Aircraft Observations
at Each Pressure-Temperature Value
-Spring-

Temperature °C	Pressure (mb)					
	350	300	250	200	175	150
≥ -35	166					
-36	45	7				
-37	38	2				
-38	83	9				
-39	[illegible]5	9				
-40	36	28		1		
-41	41	35				
-42	26	41		1		
-43	17	33	4			
-44	12	39	4	2		
-45	17	58	3	4	3	
-46	9	59	7	7	1	
-47	5	62	12	3	1	
-48	6	45	23	2	8	
-49	5	28	18	5	4	1
-50	1	39	36	13	8	8
-51	1	28	39	16	5	1
-52		10	61	9	6	1
-53		8	52	12	7	3
-54		5	70	26	15	1
-55		4	71	23	16	11
-56		3	50	18	18	15
-57		1	26	26	26	13
-58		2	27	30	22	13
-59		1	17	39	36	18
-60			7	38	36	24
-61			4	47	12	19
-62				38	14	6
-63				32	9	6
-64				23	17	4
≤ -65				26	36	8

NOTE: The temperature range inclosed between the two horizontal lines at each pressure level is the range where, theoretically, contrail formation is determined by atmospheric relative humidity.

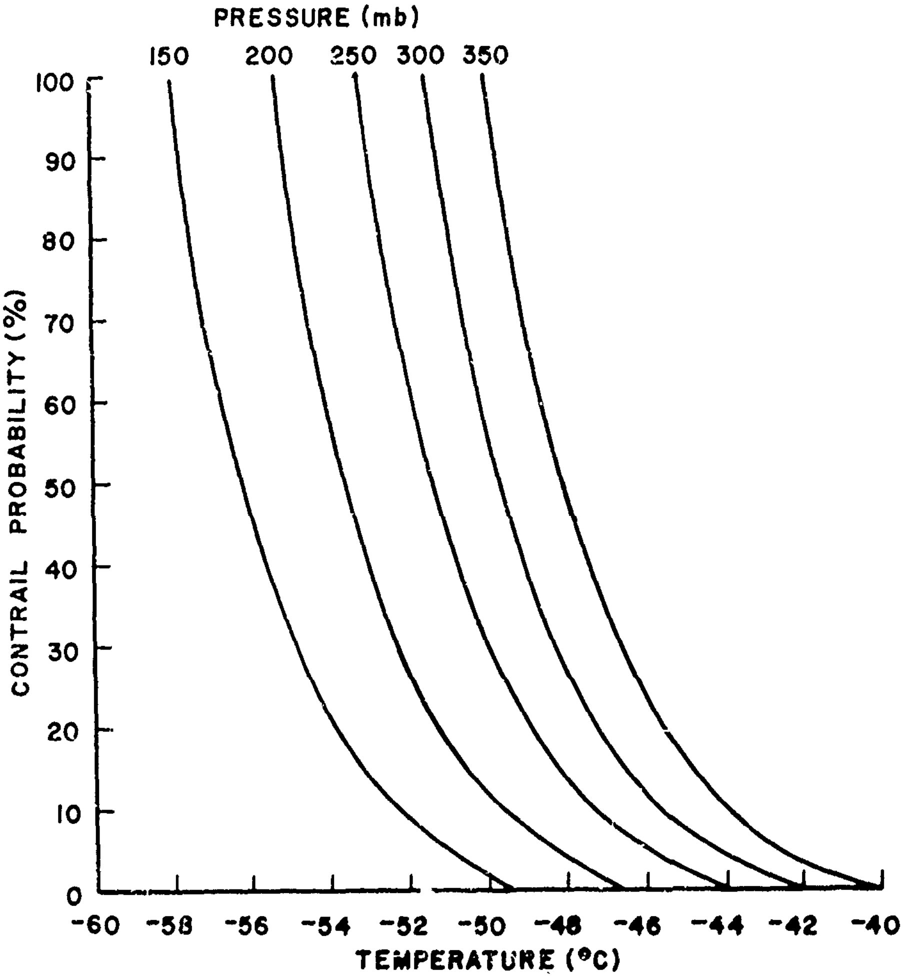

Fig. 6. Theoretical Contrail-Probability Curves. These curves are based on pressure-temperature relative humidity relationship shown in Figure 1, and assuming an equal chance of all relative humidity values for 0 to 100% for each pressure-temperature point.

. Discussion of Winter and Spring Curves

In both winter and spring, the contrail-probability curves slope upward to the left. For any fixed value of temperature, therefore contrail probability decreases with height. The usual lapse rate is much steeper than the probability curves in the troposphere, however, and less steep in the stratosphere. Consequently, on the average, contrail probability increases with height up to the tropopause, then decreases. A detailed study of this relationship will appear in the final study.

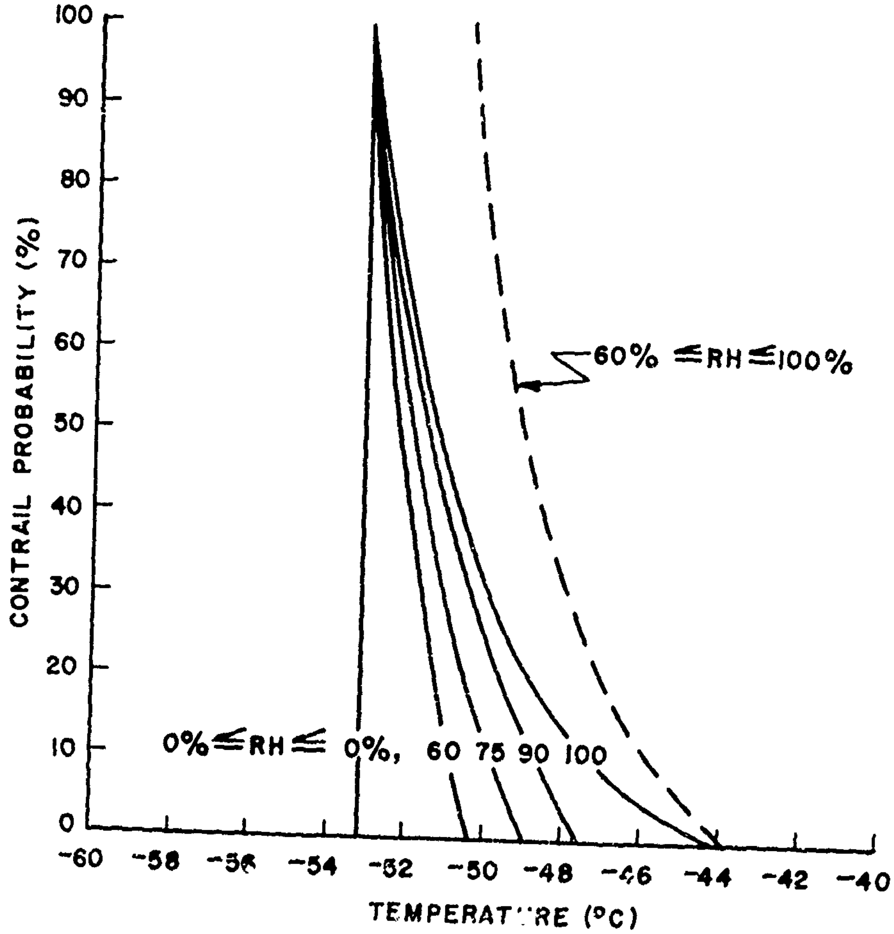

Fig. 7. Theoretical Contrail-Probability Curves for 250 mb. These curves are based on the assumption of an equal chance for all relative humidity values from $RH_{Min} \leq RH \leq RH_{Max}$.

As mentioned earlier, there is some question regarding the validity of the flattening of the upper part of the individual contrail-probability curves (Figures 2 and 3). Consequently, the lower part of each curve was extrapolated smoothly upward without inflection (dashed curves). The resulting 100% probability values can tentatively be considered as giving the true pressure-temperature relationship for 100% contrail occurrence. (Of course, all extrapolated values are to some extent subjective.) For purposes of forecasting, however, it is not desirable to eliminate errors with which the forecaster must contend under actual operating conditions. For the present, therefore, it is recommended that the solid curves shown in Figures 4 and 5 serve as the basis for probability forecasts. This problem also will be discussed in more detail in the final report.

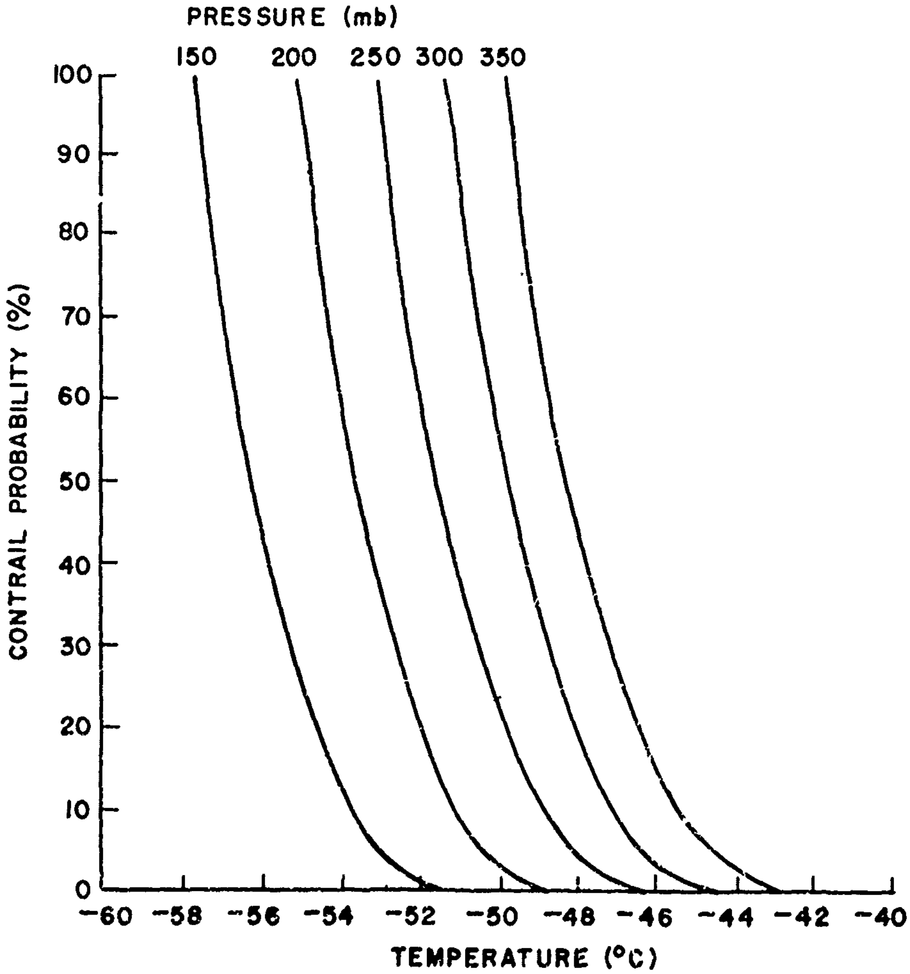

Fig. 8. Theoretical Contrail-Probability Curves. These curves are based on pressure-temperature relative humidity relationship shown in Figure 1, and assuming a normal distribution of relative humidity about a mean of 50% with a σ of 20%.

Apart from their primary use, the contrail-probability curves are of interest for the information they provide regarding the relative humidity at high altitudes. If the relative humidity were the same at all altitudes, the contrail probability curves would parallel the relative humidity curves. However, in Figure 4 it is seen that the probability curves cross the relative humidity curves toward higher values up to some altitude, then cross back toward lower values. This indicates

that on the average the relative humidity increases with height up to the critical altitude, then decreases. The critical altitude for the winter season was between 200 and 220 mb. The contrail-probability relative-humidity relationship for the spring season was similar to that for the winter season except that the critical altitude was between 150 and 175 mb. The level of maximum mean relative humidity is probably related to, although somewhat higher than, the mean height of the tropopause, which fell at 247 mb in winter and 227 mb in spring. Since it appears that relative humidity continues to increase for some distance above the tropopause, the fall-off in contrail probability above the tropopause would be less sharp than expected from the temperature inversion alone.

III. CLIMATOLOGY OF CIRRUS

With the advent of high-altitude aircraft, the importance of cirrus to military operations has increased. Navigation, refueling, bombing, and reconnaissance are among the operations which can be hampered by widespread decks of cirrostratus. Despite its importance, however, little actual knowledge has been available regarding the altitudes and temperatures at which cirrus occurs. It has long been known that visual estimates of cirrus heights are generally exceedingly inaccurate (see AWS TR 105-110). In order to increase our knowledge, it was necessary to gather a large collection of data taken from actual cirrus penetrations. This necessitated the use of high-flying jet aircraft.

One set of observations made by Project CLOUD TRAIL aircraft dealt with the bases and tops of cirrus layers as measured by actual cirrus penetrations. Since the aircraft ascents were made over radiosonde stations, accurate temperature measurements were available for all reported heights. Unfortunately, the radiosonde is unable to measure relative humidity at the low temperatures where cirrus occurs.

The statistical summary of the cirrus data, as obtained from the associated aircraft and radiosonde measurements, is shown in Tables III, IV, and V. The data were treated separately by season, latitude, and cirrus coverage. At present, studies have been completed for only the winter and spring seasons. Latitude effect was studied by dividing the stations into a northern (N) and southern (S) group, then combining them (US). The dividing line used was 39°N. Cirrus coverage also was broken down into two groups, scattered (1/10 - 5/10) and broken (6/10 - 10/10). The Table V includes mean values of the height and temperature of the cirrus bases, and thickness of the cirrus layers. In Tables III and IV the number of cases is given first, followed by the cumulative percentage in parentheses.

In general, it is seen that the cirrus occurred at temperatures near -47°C and at a height near 30,000 feet. Broken layers occurred at somewhat lower altitudes and higher temperatures, and were significantly thicker than scattered layers. Cirrus in the south occurred at slightly higher altitudes and temperatures, and was somewhat thicker than in the north. Surprisingly, there was little seasonal change in cirrus height; however, the cirrus occurred at somewhat higher temperatures and the layers were significantly thicker in spring than in winter.

TABLE III

Distribution of Observed Values of Cirrus Height, Thickness, and Temperature — Winter

	No. of Cases 1/10 - 5/10 Coverage			No. of Cases 6/10 - 10/10 Coverage		
Height (1000's ft)	N - US	S - US	US	N - US	S - US	US
	(%)	(%)	(%)	(%)	(%)	(%)
25-28	18(29)	7(25)	25(27)	28(53)	9(35)	37(47)
29-32	25(68)	9(53)	34(63)	20(91)	12(81)	32(87)
33-36	13(89)	7(77)	20(85)	2(94)	5(100)	7(96)
37-40	6(98)	5(93)	11(97)	3(100)	0	3(100)
> 40	1(100)	2(100)	3(100)	0	0	0
Thickness (100's ft)						
≤ 5	13(22)	5(19)	18(21	7(14)	0(0)	7(10)
6-15	20(56)	9(52)	29(55)	12(38)	2(9)	14(29)
16-25	13(78)	6(74)	19(77)	6(50)	6(36)	12(46)
26-35	5(86)	5(93)	10(88)	8(66)	4(55)	12(63)
36-45	4(93)	0(93)	4(93)	3(72)	3(68)	6(71)
46-55	1(95)	1(96)	2(95)	6(84)	2(77)	8(82)
55-65	2(98)	0(96)	2(98)	0(84)	1(82)	1(83)
65-75	0(98)	0(96)	0(98)	4(92)	3(95)	7(93)
> 75	1(100)	1(100)	2(100)	4(100)	1(100)	5(100)
Temperature (°C)						
-31/35	2(4)	1(4)	3(4)	2(4)	1(5)	3(5)
-36/40	2(7)	4(20)	6(11)	8(22)	3(19)	11(21)
-41/45	14(33)	2(28)	16(32)	10(44)	8(57)	18(48)
-46/50	10(52)	7(56)	17(53)	12(71)	5(81)	17(74)
-51/55	15(80)	3(68)	18(76)	7(87)	3(95)	10(89)
-56/60	7(93)	4(84)	11(90)	4(96)	1(100)	5(97)
-61/65	3(98)	3(96)	6(97)	1(98)	0	1(99)
≤ -66	1(100)	1(100)	2(100)	1(100)	0	1(100)

TABLE IV

Distribution of Observed Values of Cirrus Height, Thickness, and Temperature — Spring

	No. of Cases 1/10 - 5/10 Coverage			No. of Cases 6/10 - 10/10 Coverage		
Height (1000's ft)	N - US	S - US	US	N - US	S - US	US
	(%)	(%)	(%)	(%)	(%)	(%)
25-28	32(33)	7(22)	39(30)	25(40)	10(45)	35(42)
29-32	38(72)	15(69)	53(71)	16(66)	6(73)	22(68)
33-36	20(93)	7(91)	27(92)	16(92)	4(91)	20(92)
37-40	2(95)	2(97)	4(96)	5(100)	2(100)	7(100)
>40	5(100)	1(100)	6(100)	0	0	0
Thickness (100's ft)						
≤ 5	13(14)	6(19)	19(15)	2(3)	0(0)	2(2)
0-15	26(42)	7(41)	33(41)	7(15)	3(14)	10(15)
16-25	14(56)	6(59)	20(57)	10(32)	4(33)	14(32)
26-35	14(71)	4(72)	18(71)	11(50)	3(48)	14(49)
36-45	3(75)	1(75)	4(75)	5(58)	2(57)	7(58)
46-55	10(85)	4(88)	14(86)	5(67)	3(71)	8(68)
56-65	4(89)	0(88)	4(89)	6(77)	1(76)	7(77)
66-75	1(90)	0(88)	1(90)	3(82)	0(76)	3(80)
> 75	9(100)	4(100)	13(100)	11(100)	5(100)	16(100)
Temperature (°C)						
-35	5(6)	2(8)	7(6)	11(20)	4(19)	15(19)
-36/40	16(25)	3(21)	19(23)	7(32)	7(52)	14(38)
-41/45	14(40)	6(46)	20(41)	10(50)	3(67)	13(55)
-46/50	25(69)	6(71)	31(69)	12(71)	3(81)	15(74)
-51/55	14(85)	4(88)	18(86)	9(88)	2(91)	11(88)
-56/60	11(98)	1(92)	12(96)	6(98)	1(95)	7(97)
-61/65	2(100)	2(100)	4(100)	1(100)	1(100)	2(100)
≤ -66	0	0	0	0	0	0

TABLE V

Seasonal Mean Values of Cirrus Height, Thickness, and Temperature

	Winter					
	1/10 - 5/10 Coverage			6/10 - 10/10 Coverage		
	N - US 39°N	S - US 39°N	US	N - US 39°N	S - US 39°N	US
Height (ft)	31,080	32,810	31,640	28,920	30,470	29,430
Thickness (ft)	1,850	1,930	1,170	3,120	3,960	3,380
Temperature (°C)	-49	-50	-50	-47	-45	-46
	Spring					
Height (ft)	30,630	31,360	30,820	30,300	29,640	30,120
Thickness (ft)	3,000	3,390	3,100	4,470	4,750	4,550
Temperature (°C)	-47	-46	-47	-45	-43	-44

IV. HEIGHT ESTIMATES OF CIRROSTRATUS CLOUDS

In 1953 AWS TR 105-110, "Memorandum on Estimating the Height of Cirrustratus Clouds," was disseminated to all detachments. The estimated height is determined by the intersection of the 90% contrail-forecasting curve with the sounding. Cloud-height measurements were made by RB-47 and RB-36 aircraft on routine flights. The average absolute error, based on 102 cases, was 3500 feet. The test was limited to cloud decks above 25,000 feet.

Because of the relatively small amount of data, and the fact that the aircraft were generally flying at only a small range of elevations, it was decided to make a more thorough evaluation of the method. Project CLOUD TRAIL was the first project to provide sufficient, accurate data to allow such a study to be made. Although tests to date have not been carried sufficiently far to be conclusive, it appears as if the method gives a mean absolute error of about 3000 feet when applied to genuine cirrus layers. However, it has been found that in the warm seasons not all cloud layers above 25,000 feet are necessarily cirrus; frequently, the temperature is sufficiently high to indicate the probability that the cloud layer is altostratus. The final evaluation of accuracy will, therefore, apply only to cloud layers based at temperatures below an as yet undetermined critical value, near -35 or -40°C.

V. HIGH-LEVEL TURBULENCE OVER THE U.S.

The effects of turbulent air flow of such dimensions as to alter the smooth flight of aircraft have long been experienced in the lower levels of the atmosphere. Such turbulent flow contains elements of upward motion and an experienced pilot knows the warning signals for such conditions. He reacts to these warning signals formed by the vertical motion, such as cumulus, towering cumulus, thunderstorm and mountain wave clouds, by cutting his flying speed down in an effort to reduce the shock of the turbulence to his aircraft. This warning system is fairly successful in the lower levels since there is generally enough moisture present to allow the clouds to form most of the time.

With the coming of jet aircraft it was expected that we would now be able to fly over most of the "weather". Unfortunately, in the case of turbulence, at least, this did not prove to be correct. Turbulent air flow affecting aircraft, although probably caused by quite different factors than in the lower levels, is fairly common above 25,000 feet. At these upper levels, however, there is usually not enough moisture in the air for the relatively small vertical motions to form clouds; therefore, at the optimum altitudes for jet aircraft operations, the turbulence generally occurs without the benefit of the cumuliform cloud warning system. Thus, the jet pilot has little or no chance to slow down his aircraft and reduce the shock of the turbulence. Since the greater speed of the jet aircraft intensifies the shock of a given strength of turbulence over the effect of the same turbulence on a slower type aircraft, it is unfortunate that the high level turbulence has this insidious aspect of occurring just "out of the blue" without warning. Although this clear-air turbulence does occur below 25,000 feet, percentage-wise it is much more prevalent in the upper levels.

The turbulence associated with mountain-wave conditions can and does extend to very high levels. Even the high-level turbulence caused by this very significant

phenomenon is sometimes quite severe and warrants serious consideration. In order to avoid confusion with that high-level turbulence which occurs over flat country and ocean areas, the generally more dangerous phenomenon of mountain wave conditions will be considered separately and forecast according to rules set down by Jenkins [1], [2], Colson [3], and others. (See Figure 9.) Therefore, in the remainder of this report the emphasis will be on high-level turbulence not induced by orographic barriers.

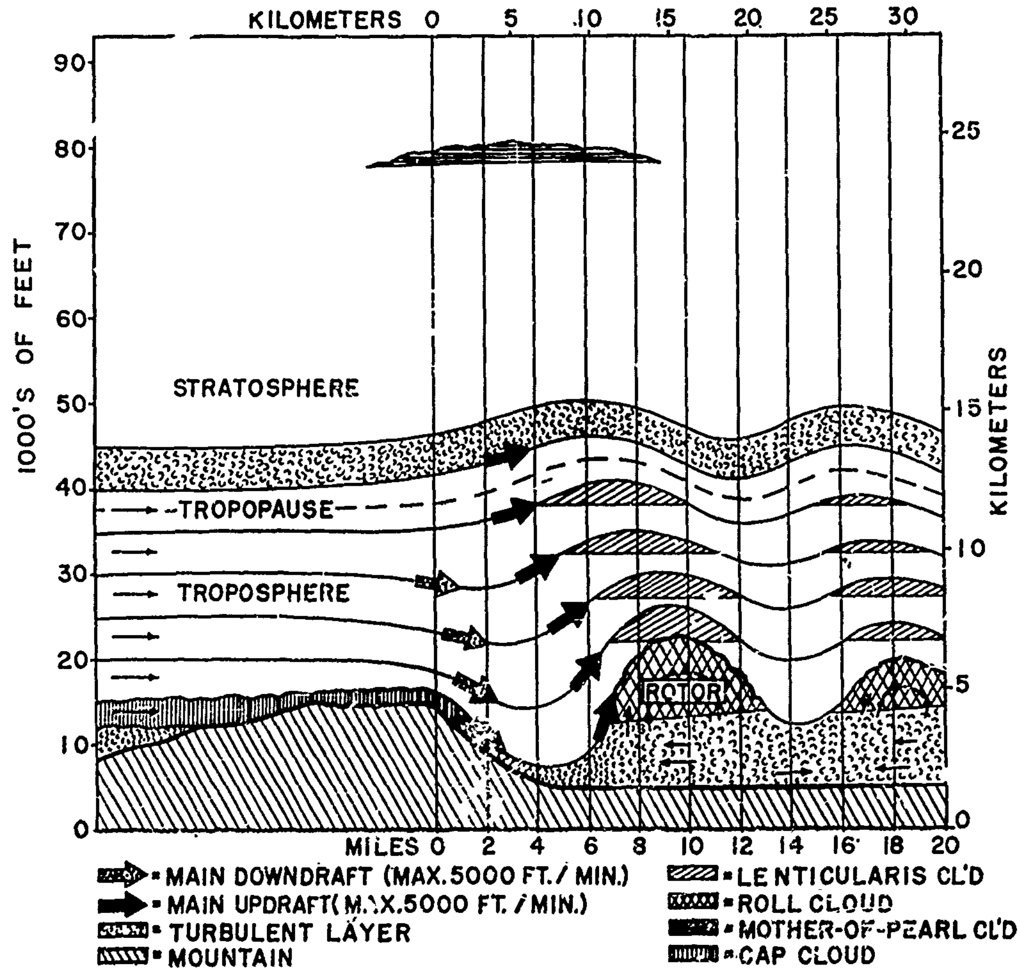

Fig. 9. A Cross Section of a Mountain Wave.

A. Nature of High-Level Turbulence

The picture of the nature and physical make up of high-level turbulence is far from crystal clear. This is understandable since it is undoubtedly possible to have more than one combination of factors capable of causing such turbulence; hence, its physical dimensions must include the whole possible spectrum, both with regard to time and space. However, we can draw some general conclusions from past research programs about the nature, shape, and size of these high-level turbulent areas and their 3-dimensional distribution. Generally, this rough turbulent air flow causes the aircraft to react in a manner similar to a fast speed-boat as it pounds over rough and choppy water or to a car being driven over an irregularly cobble-stoned surface. The areas of turbulence are generally shallow (1000-2000 feet thick), narrow in width (10-30 miles), and elongated (probably oriented in the direction of the wind), frequently being several times longer than they are wide. In horizontal distribution, the turbulent areas occur as scattered patches and are interspersed with smooth areas such that the ratio of turbulence to non-turbulence varies from 1 to 1 to about 1 to 8 or 10. In the vertical, the turbulence often occurs in multiple layers, frequently being found above, below and mainly on the cyclonic side of strong maximum-wind-speed centers that move along the jet streams [4], [5].

Although the lack of adequate upper air data, particularly during strong wind conditions, has been a serious handicap to studies attempting to relate this turbulence to stability and flow criteria; the need for learning more about this phenomenon is urgent. Therefore, high-level turbulence as an element to be reported was added to Project CLOUD TRAIL which was being developed to obtain pilot reports of the observed heights of contrails and cirrus clouds. Pilots of the Air Defense Command's interceptors from many bases in the United States participated in this program by making a climb to altitude over the rawinsonde station closest to their base at 1500Z and observing these phenomena. (See Introduction, p.1.) Thus, with some 23 upper-air sounding stations in the United States covered nearly every day and with the flights coordinated with the 1500Z soundings, some very valuable data on turbulence were collected.

B. Summary of Observational Data

The data collection phase of Project CLOUD TRAIL was started by the Air Defense Command shortly after 1 December 1954. Some of the turbulence statistics for the first four months of the program are given in Table VI.

TABLE VI

CLOUD TRAIL Reports of Turbulence by ADC Jet Aircraft

	Missions Completed	Missions Reporting Turbulence	% of Missions Reporting Turbulence	Most Intense Turbulence Reported			Layers of Turbulence	
				Lt	Med	Sev	Single	Multiple
Dec	292	131	45%	87	39	5	84	47
Jan	325	113	35%	58	45	10	73	40
Feb	274	80	29%	50	28	2	64	16
Mar	309	73	24%	38	30	5	55	
Total	1200	397	(Avg) 33%	233 (19%	142 12%	22 2%)	276	121

From these data we see that, on the average, for the stations sampled which were fairly representative of the whole United States, turbulence was encountered above 25,000 feet on about 1/3 of the 1200 missions flown from December 1954 through March 1955. However, for individual stations this figure varied tremendously both with time at individual stations and with space between stations of different geographical location. Of the missions that reported high-level turbulence, 30% encountered more than one layer of turbulence, with three layers not being unusual. Generally, the more intense uses of turbulence were associated with those missions reporting multiple layers of turbulence. However, there were many more observations of light turbulence, which also sometimes occurred in several layers, than there were of the more intense turbulence. In the data given above, only one report of turbulence was counted for each mission, and that was the most intense turbulence encountered regardless of the number of layers reported.

C. Limitations

It should be noted that these data have certain definite limitations which were unavoidable in this program. In the first place, the pilots evaluation of the turbulence was strictly subjective. Secondly, since a turbulent area is made up of patches of turbulence interspersed with generally larger areas of non-turbulence, it would be perfectly possible for an aircraft to climb right through a turbulent layer and not observe any effects of the rough air. This appears to have been the case in some situations in this study where an aircraft would climb through a region reported to be very rough by other aircraft in the general area; yet, the pilot of the original plane would observe no turbulence. This condition implies that we must think of turbulence encounters on a probability basis. Finally, since making these flights for Project CLOUD TRAIL is not the primary mission of the Air Defense Command, there were times when the weather situation was so poor that it did not warrant making the flight. There are certain well established indications that these bad weather situations may also be the times and areas when the more intense turbulence would have probably been encountered had the mission been flown. Thus, there may well be a built-in bias in the data collection phase which would reduce the number of observations of the more intense turbulence. In addition, the reported altitudes of the observed turbulence are subject to the usual errors of aircraft altimeters. Therefore, these data because of the stated limitations and bias do not lend themselves to a pure statistical analysis, and the conclusions drawn from the figures above must be viewed in this light.

D. Meteorological Aspects and Indications

In the interest of trying to associate the observed areas of turbulence with some measurable meteorological parameters, the reports of each mission flown were studied together with the corresponding distribution of wind and temperature both in the vertical and on the standard constant-pressure surfaces. The findings of this preliminary study are not concrete, but there were certain trends of indications that should be noted.

First, the occurrence of light turbulence, although much more prevalent than the more intense type, was not as clearly associated with specific synoptic situations as was the latter. The impression is given that the mildly turbulent air flow not only can be associated with a number of things but that it apparently can be propagated in space from the scene of its origin. It may frequently be the result of reflection on such interfaces as the tropopause, and it is found to be

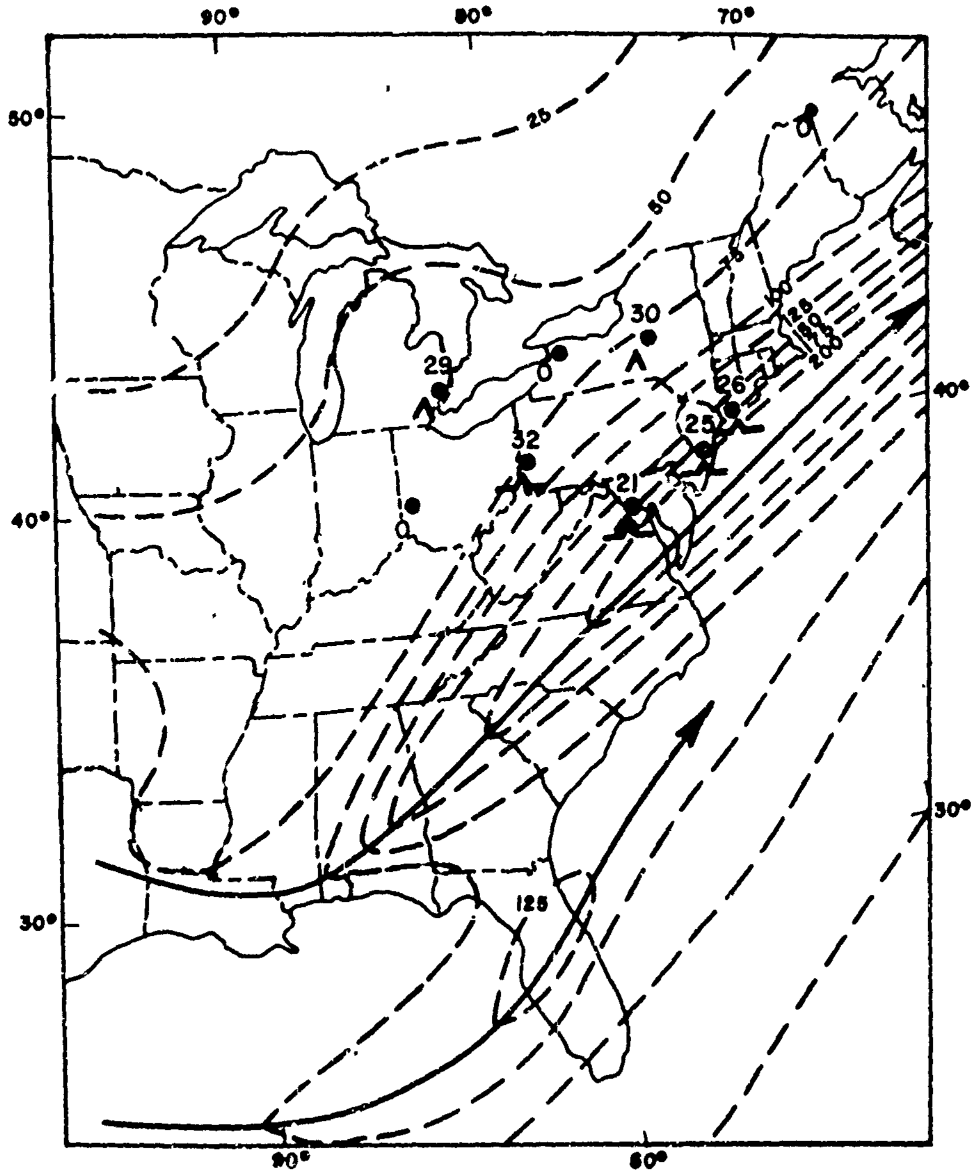

Fig. 10. Distribution of Observed Turbulence in Relation to the Jet Stream — 1500Z 24 January 1955. Dashed lines are isotachs (knots) at 300 mb. Solid lines are jet stream axes. Number above station circle is the altitude (thousands of feet) of most pronounced turbulence during climb of aircraft. Intensity of turbulence is plotted below station circle as indicated below:

0 - No turbulence reported
∧ - Light turbulence
\- Moderate turbulence
\- Severe turbulence

present well after what appears to be the stimulating force is gone. Of course, this condition may well be the final stages of more intense turbulence which is being dissipated. In view of these facts, it seems desirable to refer to the somewhat clearer association between meteorological parameters and the more intense cases of turbulence.

In the reported cases of moderate or severe turbulence, most of the time the synoptic situation was one with a strong jet stream (indicated by the 300- or 200-mb chart) either over or somewhat to the south of the station. In addition to this primary requirement, a center of high-speed winds that move along the jet stream was in the general vicinity of the station. These situations are most often associated with very bad surface weather north of the axis of the jet and under the leading half of the maximum wind-speed center. There are no quantitative rules to determine this turbulence condition but only the indication that the region was under the influence of the jet stream and the maximum wind-speed center. There appears to be a preference for this region to be below and on the north or cyclonic side of the jet maximum, but there are indications that this is not always the case. Once the constant-pressure charts have given a general picture of the preferred synoptic situation, much detail can be gained from the upper air soundings of the station itself. As a maximum wind-speed center moves in, the increase in winds aloft can be noted on subsequent soundings, and the pronounced shear zones which appear to be associated with these cases of intense turbulence are easily detected. In addition, the temperature sounding is very helpful, particularly in the absence of upper-wind data, since the turbulence frequently occurs either in or just below the tropopause inversion or other distinct variations in the lapse rate.

A minority of cases of more intense turbulence did not occur under the stated synoptic situation. In this group were included situations involving the passage of sharp trough lines (with frontal zones probably being involved) and deep cold lows with the possibility of smaller scale high-velocity winds and wind changes associated with the turbulence. There were also a few situations at certain locations which probably represented mountain waves but these were not prevalent since the stations included in Project CLOUD TRAIL were selected to keep this effect at a minimum.

As a check on these indications of which synoptic situations are associated with pronounced turbulence, the reports of missions flown through regions which were not under the obvious influence of the specific regimes mentioned were studied and found to have very few reports of turbulence. There were some exceptions, but most of the relationships were good.

Thus, it appears that one fairly reliable way of removing the unexpected aspect of a pilot running into pronounced clear air turbulence at high levels would be to forecast its probable presence whenever a jet stream with a maximum wind speed center, a sharp trough line, or a deep cold low is moving into the area.

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